

Surveillance of Space – Optimal Use of Complementary Sensors for Maximum Efficiency

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ABSTRACT

The UK has conducted a number of studies into the requirements for Surveillance of Space and the associated analysis and dissemination issues which emerge that are needed to produce a Recognised Space Picture. The UK also has existing niche capability in a number of areas related to Surveillance of Space and potential in a number of other areas that could be harnessed for this purpose. For example, use of ground-based optical sensors, phased array radar technology, radar data processing for space object identification and development of small satellites, are all areas of expertise, which have current or potential applications for Surveillance of Space.

The trends that will drive the requirements of future new or enhanced systems are briefly considered, and then the potential contribution of current and emerging technology in ground-based systems and potential space-based concepts examined. Trade-offs and synergistic operation that will need to be considered to inform any possible decision of the optimal sensor blend for future systems are set out.

The emerging satellite trends are for increased proliferation and reduction in size. This results in an increase in the number of objects which must be monitored and a reduction in the size of the smallest objects detectable. The ability to perform formation flying also calls for improved resolution and the ability to discriminate features between closely spaced objects. The emergence of dual-use systems also imposes a greater need to be able to gather information on the status and capabilities of objects.

The UK has operated a series of optical sensors for Deep Space Objects, using a number of distributed sites and optical sensors, based on COTS technologies of 10 years ago. A recent study has looked at the potential for an upgraded system using current COTS, improved processing and novel techniques. This essentially extends the remit to LEO as well as increasing the sensitivity of the system. In addition, some of the trends and technological capabilities that are emerging or have been demonstrated in radar research are summarised, and the relevant contribution to a system of complementary sensors discussed.

Whilst such a system offers the potential to address many of the emerging requirements, some cannot easily be met with a ground-based system. The paper examines which of these cannot realistically be met with ground-based sensors and considers where the synergistic or complementary use of space-based sensors could be of use. As it is seen that operating in space becomes cheaper and technology matures, this becomes a more affordable and reliable option.

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1.0 INTRODUCTION

With the increased use of and reliance on space by both military and commercial organisations, and the proliferation of the number of nations with access to space assets, the concept and importance of a Recognised Space Picture (RSP) has emerged within the UK community. This paper briefly addresses the emergent requirements and then gives a broad overview of the features and trends of the technologies that could provide the information to produce such a picture. From that the complementary use of sensors for maximum efficiency and some of the issues involved with the architecture and processing of the data is covered.

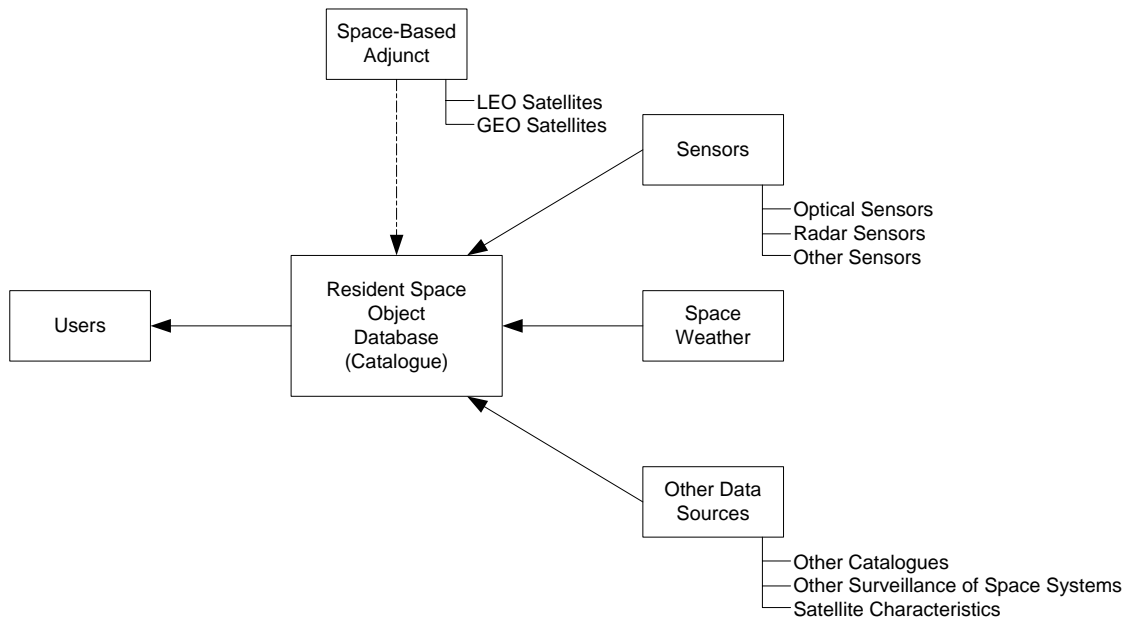


Figure 1: Generic Surveillance of Space system.

2.0 CAPABILITY REQUIREMENTS DRIVERS

The capability required to provide an effective space surveillance system which could contribute to the Recognised Space Picture will be driven by (at least) the following issues [1].

2.1 Small Object Detection

The ability of technology to provide significant capability in a small volume has allowed the development of micro-, nano- and pico-satellites. Because these satellites are small, have low manufacture costs, and have low launch costs, their use is expected to increase dramatically in the future; small objects are expected to proliferate in all orbit regimes and will be a significant challenge to any space surveillance system.

These miniaturised satellites can already provide capability in:

- Civil applications such as communications
- Earth observation including disaster monitoring
- Military peacetime observation of facilities and operations
- Wartime theatre observation

- RF emissions monitoring
- Satellite-to-satellite imaging.

While some commercial Earth observation image providers are subject to shutter-control agreements, such agreements will be difficult or impossible to arrange with all the owners of small satellites; the regulation of imaging in both peacetime and conflict will be impossible. In addition, the use of small satellites for monitoring RF emissions is anticipated to be widespread. The global military trend is for SATCOM and strategic Earth observation. Firstly with visible-band optical sensors for high-resolution imaging, then SAR imaging for all-weather performance, and finally for SIGINT applications. Clearly high resolution imaging is difficult within the small size of microsatellites without recourse to synthesised apertures, such as SAR and formation flying techniques.

Thus the growth of the small satellite population will impose a much greater need for satellite overflight warnings; services providing such warnings will need to be fed with information from space surveillance capabilities.

Table 1: Satellite classification

Category	Mass Range (kg)	Typical Size (cm)
Large satellite	> 1000	5000
Medium-sized satellite	500 – 1000	1000
Mini-satellite	100 – 500	500
Micro-satellite	10 – 100	100
Nano-satellite	1 – 10	50
Pico-satellite	0.1 – 1	10

The low weight of small satellites will enable nations to launch them without the major infrastructure required by larger satellites, so control over launches will not be possible. It will also be easier for large satellites to piggy-back small satellites into orbit and consequently it will not be immediately obvious that those small satellites are in orbit.

2.2 Growth of the Space Population

The increase in the space population and in particular the increased number and capability of smaller satellites in all orbital regimes may be expected to lead to a change in the fundamental method of surveillance of space. Currently this is largely time-shared but largely based on periodic tracking of known objects to maintain accuracy, some searching for new objects in response to particular events such as launches, and some tasking to search specific volumes. In future the emphasis may shift to be to one based more on surveying much larger volumes on both a regular and tasked basis.

2.3 Catalogue Completeness Checks

As both the capability and number of potential overflight threats to ground operations observation increases, the ability and confidence in being able to carry out unobserved activities on Earth will become more difficult. This will shift the emphasis in surveillance from reliance on intermittently updated knowledge of uncertain completeness (satellite catalogue) towards some capability to also determine object absence in particular volumes and times.

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2.4 Object Mission Assessment

Because the future space population will be more diverse (in ownership as well as function) and will be more numerous, the rapid assessment of an object's mission will be essential. This assessment will require more detailed observations of objects including signature collection and imaging.

2.5 Space Debris and Space Asset Protection

The ability to search selected volumes for space debris is necessary to support international research and monitoring efforts. In addition checking volumes of space prior to manoeuvring own assets or confirming that there are no small objects close to own space assets is also desirable to support satellite operators.

3.0 OPTICAL SENSORS

Optical sensors have the capability to provide a number of primary data products which support the generation of knowledge giving secondary products (such as orbital element sets from positional measurements). These primary and secondary products all contribute to a Recognised Space Picture; indeed, some products are essential to that picture. Primarily, optical sensors used for the Surveillance of Space are passive, this tends to give them an advantage over radar sensors at long ranges as the radar performance is described by an inverse fourth power of range as opposed to an inverse square. Their main disadvantage in the use of optical sensors for detection and orbital prediction is the restrictions on use imposed by weather, illumination and darkness constraints. LEO objects are particularly difficult for visible wavelength systems because of limited lighting / dark sky requirements. In addition imaging is demanding because of the small angle subtended by a satellite and the optical systems limited resolution, discussed in the next section. The satellite's rapid motion to the observer (up to two degrees / second) on an unpredictable path and blurring caused by turbulence in the atmosphere also leads to limitations in imaging performance.

3.1 Future Capability Specification

These capability enhancement drivers can be translated easily into a specification of future capability:

- Larger aperture sensors will be needed to provide the sensitivity needed to detect smaller objects, as well as enabling optical imaging at appropriate on-orbit spatial resolution; the image-taking requirement will drive the type of telescope mount away from the often used alt-azimuth system. The relationship between sensor aperture diameter and the size of the smallest detectable object is complex because it depends on the characteristics of the optical system, the detector, the image processing algorithms, and the relative motion of the object within the field of view. Without prejudice to the conclusions from future planned studies, it is unlikely that pico-satellites in GEO would be detectable with sensor aperture diameters less than 1 m. At present, the estimated detectable size for objects in GEO is given at Table 2, below.

Table 2: Sensor diameter and detectable size in GEO

Sensor Diameter	Minimum Object Diameter
10 cm	150 cm
40 cm	40 cm
100 cm	15 cm

The diffraction limited resolution on-orbit is given by:

$$\delta = ((0.00122R\lambda)/\phi)$$

Where:

δ is the resolution in metres

R is the range in km

λ is the wavelength in microns and

ϕ is the sensor aperture diameter in metres

A 1 m aperture sensor working at $\lambda = 500$ nm in the visible will have a resolution of ~ 60 cm on a target at 1000 km range; the resolution scales trivially with the variables.

- Wide field of view sensors will be required to survey the space population quickly enough to provide adequate orbit sampling for orbit update and to provide a high refresh rate for a Recognised Space Picture.
- Faster read-out, more sensitive detectors will be required to cope with both the need to detect small (and thus faint) satellites and the rapid survey observations.
- Better knowledge extraction tools will be needed to help users of the RSP visualise the space environment from a perspective that gives optimal meaning for their specific application.
- Space weather input to the processes underlying the RSP will be more important because of its effect on orbit evolution, especially for the smaller satellite population and its impact on satellite operability

3.2 Products from Future Optical Sensors

The basic products from optical sensors are not expected to change (being limited by the underlying physics) but there are improvements that need to be made to current capabilities if the future space population is to be monitored effectively. It should also be noted that restrictions imposed by weather, illumination conditions and sensor location will still fundamentally apply to future systems.

3.2.1 Aperture

Larger aperture sensors could provide an optical imaging capability. This together with motion effects, wireframe modelling and image rendering could produce a capability to determine physical features in detail. Some prior knowledge of the satellite structure may need to be obtained or assumed. Combining large aperture systems with spectroscopy may, when linked to a material spectral reflectivity database and again some computer modelling, produce indications of material composition of the object under observation.

In addition the greater light-collecting power will enable smaller objects (nano-sat, etc.) to be detected, and finer time resolution for photometric signatures.

3.2.2 Field of View

Large field of view sensors are needed to provide a capability to survey the space population quickly enough to provide adequate orbit sampling for orbit update and hence a rapid refresh rate for the RSP. They would also cover more orbit classes simultaneously (such as GEO, MEO, GTO and Molniya).

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Very wide-field sensors could be used for observations of high LEO objects and could provide a low-cost augmentation of capability to a radar facility.

3.2.3 Location

Optical systems tend to be smaller than equivalent radar systems, partly by their passive nature requiring no major power supplies, and partly because of the relatively smaller apertures. They can therefore be easily more easily located, and indeed re-located, and hence be deployed to cover specific areas of interest in, for example, the GEO belt.

For very wide field of view systems used for LEO monitoring, location of a sensor at low geographical latitude could provide surveillance of objects in low altitude, low inclination orbits which would never be above the horizon of any (radar or optical) sensor at higher latitudes.

3.2.4 Detector Technology and Bandpass

In the visible and near-IR wavelengths an image sensor (e.g. CCD) is usually used to collect object and background flux contemporaneously. At longer wavelengths it is usual to bolometers, with some on/off object chopping to allow subtraction of background from atmospheric thermal emission.

Improvements in detector technology could give faster refresh of the RSP (by shortening exposure times) as well as assisting in the detection of smaller objects.

Near-infrared detectors operating in the 2.2 μm and 3.5 μm atmospheric windows would extend the observing time available by allowing observations to be taken in twilight and possibly in daylight from a site with clear air (thermal IR detectors operating in the 10 μm to 12 μm region might allow observation during daytime).

3.2.5 Wavelength and Spatial Resolution Capability

Large aperture sensors with spectroscopic facilities would enable spacecraft material analysis when used in conjunction with large aperture sensors and computer models as previously described.

3.2.6 Active Systems

Laser ranging has the potential to deliver higher accuracy orbits. The UK operates one of the worlds most accurate and productive satellite laser ranging observatory, the NERC SLR at Herstmonceaux, England. This uses retro-reflectors on co-operative spacecraft for accurate orbit measurement for a variety of satellites including navigational and calibration.

3.2.7 Imaging Techniques

Techniques used for improving imaging from ground based systems include:

- Lucky imaging
- Low-order wavefront correction with active and / or adaptive optics
- Various speckle techniques
- High-order wavefront correction using laser guide stars

Continued research and development in these techniques should allow improved and more reliable effective resolution by overcoming atmospheric blurring which occur even on sites chosen for good atmospheric properties. Employing them may allow a wider variation in the sites considered suitable.

4.0 RADAR

4.1 Capability Requirements Drivers

Surveillance of Space has a number of requirements outlined above, which actually make conflicting demands on the sensor systems, including:

- Continuous search over a large volume
- Detection of small objects, with a low false alarm rate
- Detection of small objects possibly close to large objects
- Accurate tracking for classification of objects
- Highly accurate tracking for orbital prediction of objects of interest
- Characterisation of objects is highly desirable
- Ability for specific tasking and associated restricted volume search and track, interleaved with the other tasks

Such a set of conflicting demands would tend to lead to a demand for a system with maximum flexibility.

In addition, if a system of sensors of varying attributes is considered, the ability to hand information on one track to another system is required (cueing). This translates to an ability to perform specific small volume searches, tailoring the time taken and the waveforms used to match information on the object's size and track uncertainty.

4.2 Current Systems

Radar systems have for many years been the mainstay of surveillance of near space. In many cases this has been as a subsidiary or adjunct function to ballistic missile warning or defence sensors. The primary task of such systems are to maintain search fences, defining specific volumes in space (normally just above the horizon) in terms of a set of specific, overlapping beam positions which have to be re-visited at a certain rate to ensure that objects with greater than a given radar cross section (RCS) and angular transit rate would be detected. Once detected, objects are tracked at sufficient rate and for sufficient time for kinematic classification (missile, aircraft, balloon etc), and if a ballistic object, further tracked to determine such parameters as predicted impact point and launch point. Naturally these radars would also detect and track satellites as they traversed the fence. During peacetime the radar resources may additionally be exploited (if not required for primary surveillance and tracking) to determine more information on all or more likely selected objects, higher pulse repetition frequency (PRF) may be exploited to allow analysis of variations in RCS to give insight into the object micro-motion and complexity.

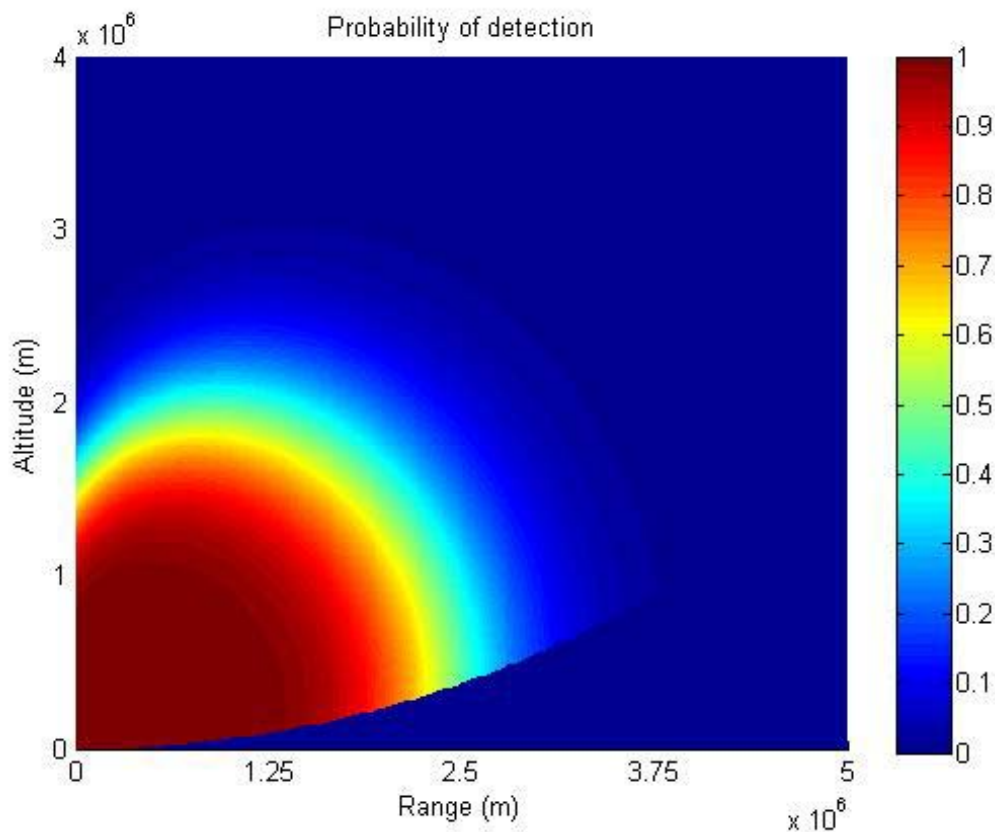


Figure 2: Search detection coverage of a generic 1 MW UHF radar

Where additional information to kinematic and RCS estimate is desired, specific radar techniques or systems may be employed. Radar with sufficiently high bandwidth to resolve individual scattering centres can be used to create one dimensional high range resolution images. If an object is moving to create a change of aspect angle, this can be exploited together with high resolution in the Doppler-frequency domain to provide cross-range resolution and hence two dimensional images can be obtained (ISAR - Inverse Synthetic Aperture Radar).

Because of the requirement of radar to perform a number of contemporaneous functions, with differing optimal radar waveforms (pulsewidth, modulation, PRF etc.) for each, multi-function phased arrays, such as the BMEWS at RAF Fylingdales have been used. Indeed the first modern phased array radar could be considered to be the AN/FPS-85 satellite surveillance radar at Eglin AFB, California [2]. A phased array radar has a fixed face, but multiple transmitting elements. Control of the relative amplitude and phase of these allows the beam to be shaped and steered in the desired directions for the desired time (dwell time). It can be seen that at any time there may be a number of tasks which could be performed and the importance or urgency of the task may be highly variable depending on the situation. Key therefore to the performance of the radar is the way in which the time between tasks is managed and shared.

The desire for high bandwidth (for both object resolution and radar imaging) has led to higher frequency mechanically scanned radar used more specifically for radar space object identification, such as the TIRA radar at FGAN in Germany. One drawback of phased array radar is the constraint on instantaneous pulse bandwidth given by beam steering. However techniques are now becoming available which can overcome this.

4.3 Future Trends in Use of Radar for Surveillance of Space

Many advances in radar research and technology are able to be exploited within future radar elements of a Recognised Space Picture architecture. The UK radar technology demonstrator programme MESAR 2 and the future ARTIST have and will investigate many of these.

4.3.1 Phased Array Technology

Advances driven by the communications sector have given rise to use of new semiconductor materials to produce elements with greater power, giving high peak power capability. In addition greater use of computing power and digital phase shifting is leading to digital beam forming. The output from the array is digitised and processed in a number of independent channels which will allow the control of groups of elements (sub-arrays) to form simultaneous multiple directive beams. A number of the emerging requirements may be addressed by use of a spoiled (broadened) transmit beam and processing multiple simultaneous receive beams. This will allow large volumes to be searched whilst maintaining the ability for angular resolution and searching for many objects simultaneously. Also, in effect, the search beam pattern may dwell for longer times in a particular direction.

4.3.2 Pulse Integration and Doppler Processing

Longer dwell time in turn will allow processing techniques to be applied to group of pulses. Incoherent integration of the pulses will increase effective signal to noise ratio and therefore probability of detection and monopulse angular measurement accuracy. Coherent processing can also be processed in the frequency domain to obtain Doppler frequency and hence object radial velocity information. Given sufficient Doppler resolution and PRF, indication of whether an object is spinning may be possible. It should however be noted that short term ionospheric fluctuations may limit the number of pulses that can be processed in practice.

4.3.3 Synthetic Wide Bandwidth

Use of multiple pulses with specific frequency modulation from pulse-to-pulse within the burst may be used to produce synthetically high bandwidth. Techniques such as stepped frequency and jump burst, illustrated in Figure 3, have demonstrated high resolution range profiling over long dwells.

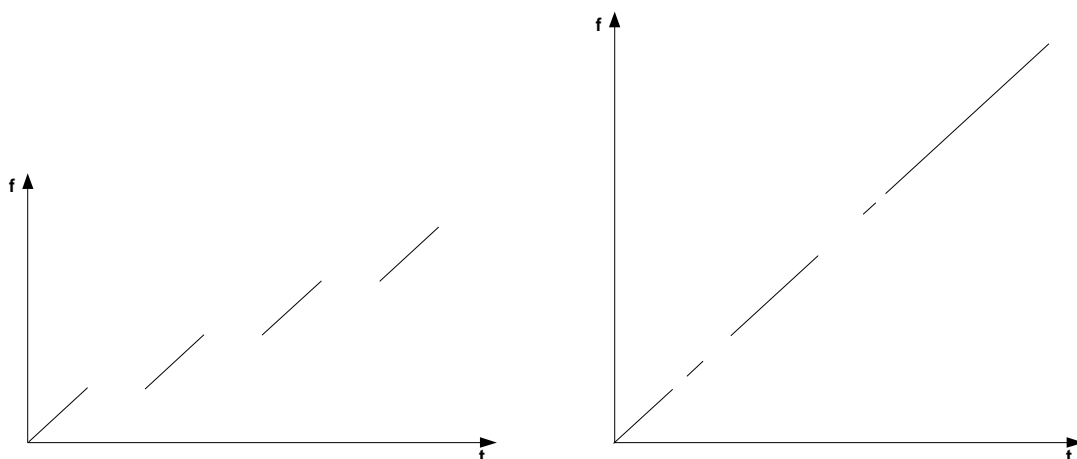


Figure 3: Stepped Frequency and Jump Burst waveforms

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4.3.4 Adaptive Radar Resource Management

To fully exploit some of these techniques, in particular when dealing with a number of objects simultaneously and also requiring perhaps to maintain background surveillance, means that the radar must adapt its parameters according to the way it sees the environment and current tasking. To do this optimally requires intelligent management of the radar resources and much research is being carried in this area in the UK and other places, and both fixed rule based algorithms and fuzzy logic approaches have been shown to be viable [3].

4.3.5 Polarisation Discriminants

Radars that view targets through the ionosphere are subject to effects such as Faraday rotation caused by the total electron content of the viewing path, which can lead to losses and distortions of the measurements. To alleviate these effects, as well as calibration, the radars tend to use dual or circular polarisation. Whilst not commonly used it may be possible to exploit the variations of return in separate polarisation channels to obtain indications of object spin and complexity.

4.3.6 Signal Processing

As well as pulse integration, other techniques of signal processing being used in other applications may be of use for future Surveillance of Space radar. Such techniques as track-before-detect [4] have been shown to allow improved sensitivity. This technique employs fast running algorithms and computing power to pre-integrate returns from objects moving over a range of particular speeds

4.3.7 Frequency and Geometry Diversity

Using sensors at different frequencies and at different viewing geometries can bring extra information to the system. The radar cross section of an object decreases rapidly once its size becomes less than the wavelength of observation (Rayleigh region) and hence better information on small objects can be obtained from higher frequency sensors. Radars are very good at measuring range, especially when employing frequency modulation for pulse compression, however, even with monopulse processing they can only get to fractions of the beamwidth in angle. This can make for large measurement uncertainty at long ranges; viewing from different ranges will improve this accuracy. Alternatively, the use of co-located optical sensors, which have good angular but no range capability, could be considered.

5.0 SPACE SEGMENT

5.1 Requirements

The preceding brief review indicates that ground-based assets have considerable capability for many of the requirements for the Surveillance of Space; however there are two areas that do not appear to be able to be addressed from the ground:

- Imaging of GEO objects
- Very detailed viewing of LEO objects to determine the status and pointing direction of individual sensors.

5.2 Space Segment

Detailed consideration of the potential capability of a space-based contribution and the trade-offs involved is complex and beyond the scope of the current paper, although the recent emergence of much smaller satellites has enabled UK to consider space-based space surveillance applications as a cost-effective

complement to ground-based surveillance of space sensors. A recent unclassified study, completed as part of the requirements for an MSc course, has looked at the issues of using space-based sensors for high resolution of imaging of GEO objects, and considered the trade-off and performance of different imaging technology. This study concludes that within certain constraints and assumptions, a useful contribution to the Surveillance of Space from space-based sensors is entirely possible using optical or radar methods [5].

6.0 COMPLEMENTARY SENSORS FOR FUTURE RSP

6.1 Sensor Blend for Conceptual RSP Architecture

This section now considers the blend of sensors that might ideally contribute to the future conceptual architecture of a Surveillance of Space system which would seek to exploit the advantages of individual sensor types to improve overall effectiveness and ability to fulfil the emerging requirements. In practice, of course, cost and other constraints make it likely that only a small part would be achievable by most nations individually, however collaboration between nations could be used to provide sources from a number of feeds.

Possible contributing sensors and their complementary use are;

- Low frequency (UHF) multifunction phased array radar for searching pre-defined and tasked volumes for detection, initial tracking and characterisation of LEO objects. These could be supplemented by wide and very wide field of view optical sensors for high LEO objects and other orbit classes such as HEO. Optical sensors could also be used for low inclination orbits. SOI could be provide by both systems
- Higher frequency (S-Band or X-Band) multi-function phased array radar which could be cued to objects of interest and provide high accuracy tracking information on a number of these simultaneously. Specific objects could also be subject to high range resolution, polarimetric or radar imaging techniques. Again these may be supplemented by optical sensors with spectroscopic resolution capabilities.
- Laser ranging capability for higher orbital accuracy measurement of appropriate systems.
- Optical systems located to provide coverage of the GEO belt at locations of specific interest, such as where the host nation or organisation has space assets. Deployable assets may also be kept in readiness for flexible response.
- Space-based high resolution platforms to provide imaging capability for GEO objects.

6.2 Incorporating Future Capability into a Conceptual RSP Architecture

Considering the overall architecture, there will be a need for a flow of data products and analysis knowledge from the sensors into the databases to inform the generation of the RSP as well as a flow of user requirements back to sensor operators and developers to enable appropriate tasking and capability of the sensors to ensure accurate and timely information is available. The structure of the RSP architecture will need to accommodate the following:

- Non-tasked surveying work which will be carried out on a continuous scan basis and which will result in observations which will need to be correlated against the RSP catalogue before contributing to orbit updates in the RSP
- Specific tasking for high priority objects (e.g. conjunctions and new launches) where some of the tasking will be automatically generated by an RSP housekeeping system and the rest will be operator initiated

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- A sensor-by-sensor decision on the nature of contributions (just primary products or primary and secondary or just secondary ?) which will affect the distribution of analysis work within the RSP environment
- A source of prioritisation which prescribes types of tasking (routine metric, SOI collection, etc.) and type of post-observation analysis as a result of knowing what product requests exist
- Archive access for tasking scheduling
- User-specified generic prioritisation (for specific satellite families) so that future information demands can be serviced with an appropriate background of information (i.e. to ensure archive completeness)

A comprehensive archive to feed knowledge-extraction and data mining tools, with data fusion as appropriate (e.g. linking optical signature behaviour with manoeuvre habits)

6.3 Data Fusion

Using co-sited radar and optical sensors would provide data fusion opportunities.

- Optical or radar sensors with wide field of view can be used as a target locator / cue for narrow field of view configurations.
- Accurate range and range-rate information from radars complements the accurate angles only observations from optical sensors.
- High resolution images from radar and optical sensors show different object features and so provide complementary information about an object.
- Improved SOI from combination of information based on common physical characteristics observed in different bands
- Separation of sites of multiple radar or optical systems will provide a different geometry and may improve accuracy

Table 3: Fields of view and pixel size description

Attribute	Quantification
Narrow field of view	$< 1^\circ$
Wide field of view	1° to 10°
Very wide field of view	10° to 30°
Ultra wide field of view	$> 30^\circ$
Small pixel CCD	Pixel size $\sim 7 \mu\text{m}$
Standard CCD (e.g. EEV detector)	Pixel size $\sim 13 \mu\text{m}$
Large pixel CCD (e.g. Tektronix detector)	Pixel size $\sim 20 \mu\text{m}$

7.0 CONCLUSIONS

Compiling and maintaining a Recognised Space Picture is a difficult task because of the emerging trends of increased proliferation and smaller size of satellites. This may lead to a fundamental change in the method of surveillance of space, shifting the emphasis from tracking to surveying. However the complementary use of a number of sensor types, exploiting current technological capabilities and using data fusion could provide a very effective and capable solution. This paper has briefly looked at some of the trends and issues involved. In practice, few single nations may have the resources to provide all of these assets but by combining information and sources in an appropriate manner capability may be built up.

UK research activities are aimed at developing the concept and in the long term implementing a recognised space picture. This is currently focussed on developing an understanding of the requirements, concepts and trade-offs whilst aiming to investigate performance issues and building some capability through low-cost COTS based demonstrators in areas where the UK niche capability resides.

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Recognised Space Picture

- Space is becoming increasingly important to both military and commercial organisations for;
 - Communications
 - Navigation
 - Surveillance
 - Etc
- It is also increasingly important to have good situational awareness of space
- In UK the concept of a Recognised Space Picture is emerging as part of the Joint Operational Picture



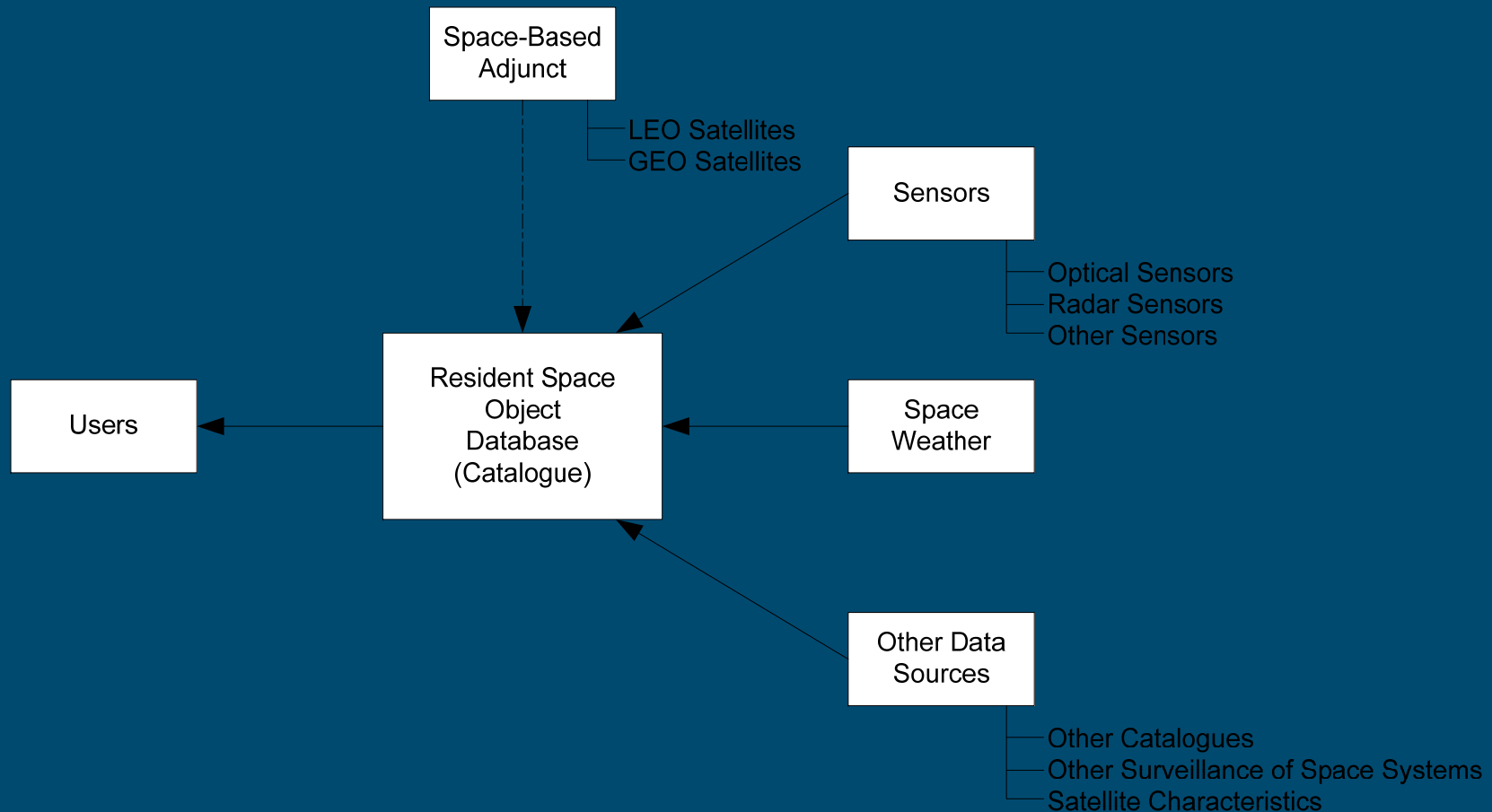
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Generic RSP architecture



Requirements (1)

- Small Object Detection

- Micro-, nano-, pico-satellite technology is rapidly maturing
- Need to be able to observe objects as small as (smaller than?) 10cm
- Proliferation of increasingly small and relatively capable satellites
- Launch and deployment more difficult to determine

- Growth of Space Population

- Proliferation of nations with access to space and more affordable systems
- May change the balance of SoS and fundamental change in method of surveillance from tracking to surveying
- Emphasis on large volume tasked and regular surveillance



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Requirements (2)

- Mission assessment
 - Rapid assessment of satellite intent will become more important with growth of numbers and diversity of space objects
- Space Debris and Asset Protection
 - Support international research
 - Confirm no objects close to valuable assets, or in volumes for planned manoeuvre

Sensor Trade-offs

- Passive (optical) sensors have inherent performance advantage over active (radar) at long ranges
 - Inverse square compared to inverse fourth power
- Optical sensors are more affected weather / illumination restrictions
- Passive optical sensors can measure angle very accurately, but no direct measurement of range
- Radar characterised by accurate range (pulse compression techniques) but more limited angular accuracy
- Images can be obtained by radar as well as optical sensors using ISAR techniques
- Other measurements such as signature variation can yield useful information but must be analysed, often in association with modelling and a priori knowledge



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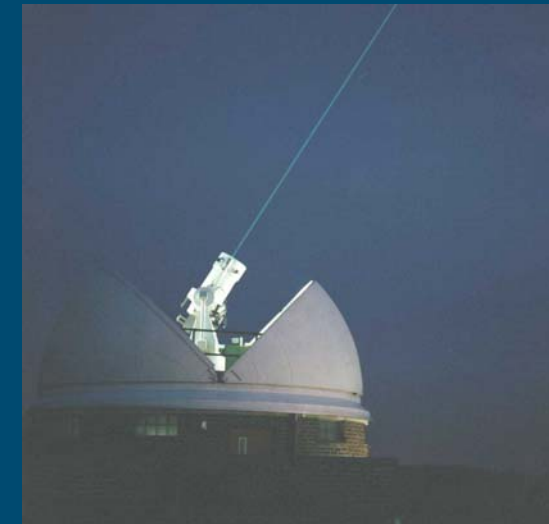
Optical Systems - UK Experience

- PIMS (Passive Imaging Metric Sensor)
 - Originally RGO dedicated inexpensive COTS space surveillance sensor
 - Herstmonceaux, Gibraltar and Cyprus
 - Unmanned and operated remotely
 - 0.4m Schmidt-Cassegrain telescope with CCD detector
 - Angular position calculated astrometrically from background stars
 - Orbital determination and photometric light curve SOI
 - Routine surveillance and specific tasking
 - Orbits above LEO
 - Currently defunct



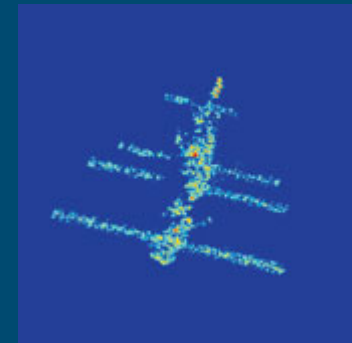
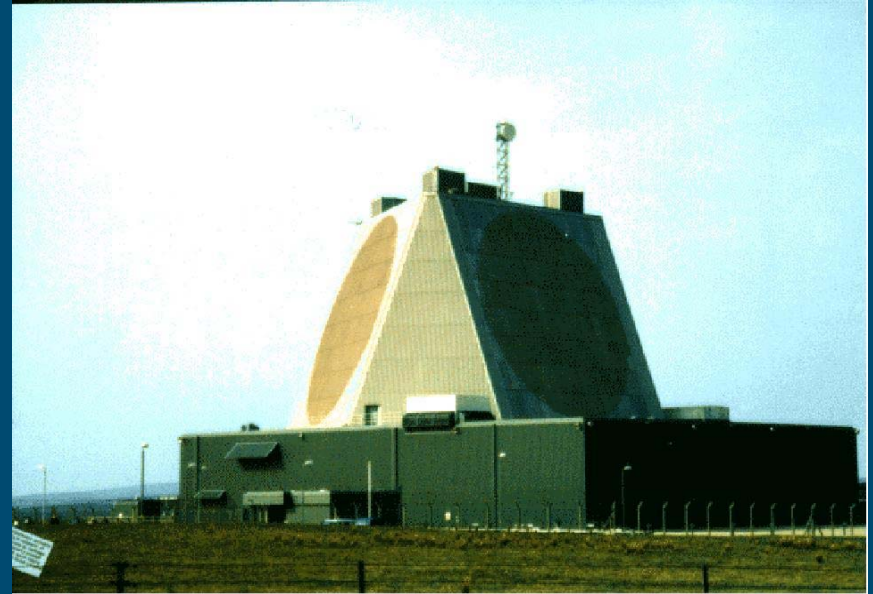
Optical Systems

- PIMS-FX Demonstrator
 - 10 cm aperture refractor lens system for wider field of view
 - Improved search and survey capability
 - 4 degree FOV could survey zero inclination GEO belt in 3 hours
- SLR Satellite Laser Ranger
 - NERC facility
 - Highly accurate, efficient and productive
 - Requires co-operative satellite retro-reflector



Radar Systems – UK experience

- RAF Fylingdales
 - Operation and use for spacetrack and SOI of the US BMEWS (UHF) radar in secondary mission
 - Satellite Warning Service UK
- Satellite tracking radar
 - Chilbolton / Defford
- ISAR image processing



Radar systems – UK research

- MESAR2
 - Phased array technology demonstrator (S band)
- ARTIST
 - Joint UK / US programme for further developing techniques and algorithms for phased array MFRs
- Considerable research into
 - Adaptive resource management
 - Advanced signal processing
 - Ionospheric effects etc
 - Systems analysis and performance assessment



Future Optical Sensors Trends and Improvements

- Aperture
 - Increased aperture for better sensitivity and imaging
 - In combination with wireframe modelling and motion effects may determine physical features
 - Improved resolution of photometric signatures
- Field of View
 - Larger field of view for faster update and RSP refresh rate
 - More orbit regimes covered
 - Very wide FOV for low cost augmentation of radar for high-LEO



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Future Optical Sensors Trends and Improvements

- Location
 - Tend to be small and can be located to cover specific areas of interest (e.g. specific longitudes of GEO belt)
- Detector Technology and Bandpass
 - Faster refresh rate (shorter exposure time)
 - Smaller object detection
 - Near and Thermal IR to increase operation times to twilight / daylight
- Spectrometry
 - Possibly used for material analysis in combination with large apertures and appropriate modelling and database

Future Optical Sensors Trends and Improvements

- Active Systems
 - Satellite laser ranging on co-operative systems
- Improved Imaging techniques
 - Improve products, viewing time and possibly choice of location if techniques can overcome atmospheric blurring
 - Lucky imaging
 - Low-order wavefront correction with active / adaptive optics
 - Various speckle techniques
 - High-order wavefront correction using laser guide stars



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Future Radar Trends and Improvements

- Use of multi-function phased arrays for SoS
 - Maximum use of flexibility
- Phased array technology
 - Higher peak power
 - Digital processing and sub-array architecture for spoiled beam and multiple receive beams
- Pulse Integration and Doppler processing
 - Better sensitivity, accuracy and information (spin / rotation)



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Future Radar Trends and Improvements

- Synthetic High Bandwidth
 - Pulse burst processing for high range resolution and profiling
- Adaptive Radar Resource Management
 - Rule based or fuzzy logic to maximise use of radar time and extraction of information
- Polarisation Discrimination
 - Indication of spin
- Signal Processing
 - Improve sensitivity to objects of interest
- Frequency and Geometric Diversity



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Space Segment

- Some requirements very hard to address from ground based sensors
 - Imaging at GEO
 - Very detailed viewing of features at LEO to determine status of sensors
- Emergence of much smaller satellites
 - Space-based space surveillance applications may start to be cost-effective complement
 - Studies have shown feasibility of both optical and radar systems



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Conceptual Sensor Blend for Future RSP

- Low frequency (UHF) multifunction phased array radar for LEO surveillance and initial tracking
 - Supplemented by wide and very wide FOV optical sensors for high LEO / HEO
- Higher frequency (S-Band or X-Band) multi-function phased array radar, cued for high accuracy tracking
 - Synthetic wideband techniques / HRR / ISAR
 - Supplemented by optical sensors with for example spectroscopic resolution capabilities
- SLR for high accuracy measurement of appropriate objects
- Optical systems located to provide coverage of the GEO belt / deep space at locations of specific interest
 - Possible re-locatable systems for flexible response
- Possibly space based system for imaging of GEO objects



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Conceptual RSP Conops

- Continuous, routine surveillance for comparison with existing RSP catalogue
- High priority tasking,
 - Part RSP automatically generated (updates) and part operator initiated (new launches etc)
- Sensor by sensor decision and tasking of inputs
- Prioritisation of type of tasking (routine, metric, SOI..) and analysis
- User prescribed tasking for specific objects and classes of objects
- Archive access for future planning / scheduling
- Collision and re-entry warning



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Data Fusion

- Wide FOV (optical or radar) sensors can be used to cue narrow FOV radar configurations
- Accurate range / range-rate from radars combination with accurate angles only observations from optical sensors
- HRR from radar and optical sensors show different object features
- Improved SOI from combination of information based on common physical characteristics in different bands
- Separation of sites of multiple radar or optical systems for geometric diversity



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Conclusions

- Compiling and maintaining RSP is very demanding task especially with growth / change of satellite population
- Complementary use of sensors, exploiting emerging technology and trends and data fusion can provide capability
- In practice ideal blend may be too demanding for most nations but collaborative solutions may apply
- UK research programme aimed at better understanding of requirements, trade-offs and issues
 - Possible technology demonstration may grow capability



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Questions ?



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